Evaluation of SeaWiFS Optical Products in Coastal Regions

In-Situ *Optical Absorption and Scattering Measurements Are Used to Develop and Validate Satellite Algorithms*

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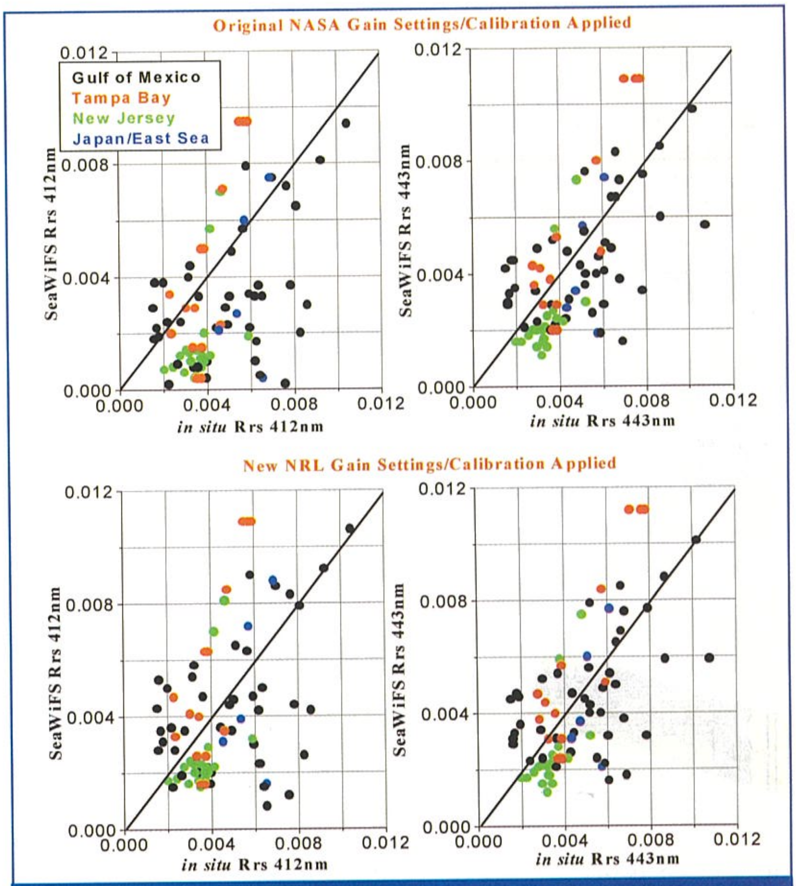


SeaWiFS-derived versus R_{rs} at 412 and 443 nanometers for each region (different color) and two sets of calibration coefficients. Black line represents 1:1 line.

We applied satellite optical algorithms to SeaWiFS (sea-viewing wide field-of-view sensor) imagery to derive inherent optical properties (absorption and scattering coefficients) in coastal and open-ocean waters. The processing employed a near-infrared (NIR) atmospheric correction[1] with a coupled ocean-atmosphere algorithm. These corrections in coastal waters enabled us to extend estimates of SeaWiFS-derived optical properties well into the bays and estuaries where high sediments and colored dissolved organic matter (CDOM) absorption dominate the optical signature. Coastal optical properties are more complex and differ greatly from chlorophyll-dominated open-ocean waters. We applied an iterative vicarious sensor calibration to SeaWiFS that consisted of adjusting the default gain settings, reprocessing SeaWiFS imagery, summing up the ratios (derived/*in-situ*) for all stations, and taking the average of all sums for each of the six SeaWiFS wavelengths. We repeated this procedure until the average approached one. This calibration forced the SeaWiFS reflectances to match the *in-situ* data, which eliminates sensor calibration and atmospheric correction errors from contributing to the errors produced by the satellite optical algorithms. The measured absorption and scattering coefficients were compared with the satellite-derived values for two optical algorithms (Arnone et al.[1] and Carder et al.[3]) in four regions (northern Gulf of Mexico, Tampa Bay, New Jersey, Japan/East Sea). Results show that satellite-derived optical properties of absorption and scattering tend to be lower than the *in-situ* measured values for both algorithms over all regions and wavelengths by approximately 49 percent and 59 percent, respectively. In addition, the Arnone et al.[1] algorithms generally yielded slightly lower errors and higher values than the Carder et al.[3] algorithms, for the average percentage of both absorption and scattering coefficients (46 percent versus 52 percent for absorption and 55 percent versus 63 percent for scattering) over all regions and wavelengths. For both algorithms, the errors in turbid (higher absorption and scattering coefficients) were similar to the errors in clear waters.

Table 1. *In-situ* **stations used in validation effort.**

Region	Number of Stations
Northern Gulf of Mexico	44
Tampa Bay	15
New Jersey Coast (LEO15)	19
East Sea	4

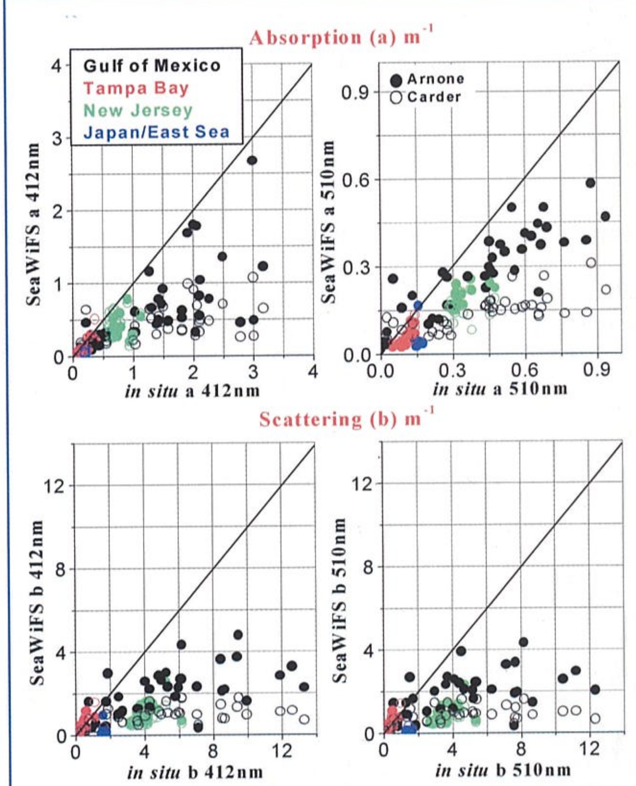
Introduction

Remote sensing algorithms for ocean color visible imagery are based on relationships between remote sensing reflectance (R_{rs}) and inherent optical properties of absorption and backscattering. We will use *in-situ* R_{rs} measurements, collected with an analytical spectral devices (ASD) fiber-optic field spectroradiometer, to vicariously calibrate the SeaWiFS sensor. SeaWiFS is a multispectral sensor containing six visible channels and two NIR channels for atmospheric correction that provides daily repeat coverage and one-kilometer spatial resolution. We will use measured absorption and scattering values collected with a WetLabs AC9 instrument to validate satellite optical algorithms[1,3] applied to SeaWiFS. Finally, our objectives are to establish a protocol to compare satellite and *in-situ* optical properties; assess errors between measured and satellite-derived values (reflectances, absorption and scattering coefficients); optimize SeaWiFS calibration vicariously using *in-situ* R_{rs} measurements; and compare optical properties derived from SeaWiFS with measured values to assess errors in the bio-optical algorithms.

Background

We assembled a database of *in-situ* optical properties and above-water reflectance measurements from 12 cruises in coastal and open-ocean waters in the Gulf of Mexico, the northeast Atlantic Ocean off the U.S. east coast and in the Japan/East Sea for comparison with SeaWiFS-derived properties. Data were collected from 1997 to present in a variety of coastal regions (Mississippi Bight, Mississippi River Delta, West Florida Shelf, Loop Current and Great Bay, New Jersey). We collected data at 328 stations covering 73 cruise days in Case I (clear) and Case II (turbid) waters.

Of the possible 328 stations, only 82 successful satellite/*in-situ* match-ups were used for this validation effort due to a variety of problems. For example, some stations collected very close to the coast were flagged as land pixels in the imagery, precluding comparisons for those stations. Other problems included cloud-contaminated satellite pixels; failure of the SeaWiFS atmospheric correction algorithm for some bay, estuary and coastal stations; invalid field reflectance spectra due to sun glint and/or surface



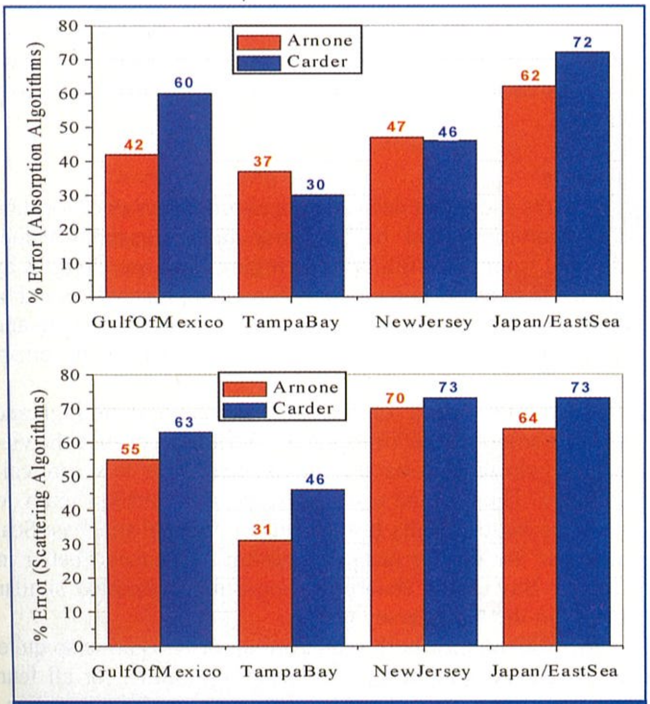
SeaWiFS-derived optical properties (absorption and scattering) versus in-situ (AC9) optical properties (absorption and scattering) at 412 and 510 nanometers for Arnone et al. and Carder et al. bio-optical algorithms. Black line represents 1:1 line.

roughness effects; erroneous optical measurements; and instrumentation problems. We also confined our comparisons to satellite/*in-situ* match-ups that were separated in time by no more than two hours.

SeaWiFS imagery was obtained from the Naval Research Laboratory's (NRL) land-based satellite receiving station, NRL's shipboard receiving station or from the NASA Goddard archive. All scenes corresponding to the dates of *in-situ* data collection were obtained, but not all were successful match-ups for the reasons mentioned above.

Once candidate scenes were collected, each was hand-navigated (to improve geo-location along the coast) and sub-sectioned using the SeaDAS software developed by NASA. The sub-sectioning reduced the image to the smallest size that covered the region of interest (i.e., the region covering the shipboard data), simply to minimize the total processing time of the satellite data. We performed an initial processing of all SeaWiFS scenes using default calibration coefficients (gains) provided by NASA. These gain values are the standard calibrations based on data collected at the MODIS Optical Buoy (MOBY) in extremely clear Case I waters off the coast of Hawaii. The MOBY waters are much different and less optically complex than the water types with which we are dealing. Because of this, we will apply SeaWiFS calibration coefficients tuned using *in-situ* R_{rs} measurements collected in Case I and Case II waters in our regions of interest.

Next, we extracted R_{rs} values from the images for each station location using the average of a 3 x 3-pixel box centered on that station location. Then, we compared the SeaWiFS-derived R_{rs} values from each station to measured values. By summing up the ratios (derived/*in-situ*) for all stations and taking the average of all sums for each of the six SeaWiFS wavelengths, we can determine the error in the sensor calibration (sum of ratios for each wavelength should be as close to one as possible).



Arnone et al. and Carder et al. absorption and scattering algorithm errors averaged over all wavelengths and for each region.

After that, we iteratively adjusted the gains, reprocessed the imagery, extracted values and re-calculated the ratios until the averages approached one. The gain settings for the NIR channels (7, 8) were not adjusted; the atmospheric correction algorithm depends on these NIR bands for selection of the appropriate aerosol model. Using the newly obtained NRL gain settings, each SeaWiFS scene was then processed using an iterative NIR atmospheric correction[1] in NRL's Automated Processing System (APS).[2]

The above-water measurements of R_{rs} were collected using an ASD field spectroradiometer and processed using NIR surface glint removal algorithms.[4] This correction is required at coastal stations to account for the remote sensing reflectance at NIR wavelengths in turbid, high-scattering waters. The ASD measures the spectrum of water-leaving radiance (and surface reflection) at 1.3-nanometer resolution from 330-1,100 nanometers. A gray card of known reflectance (12 percent Spectralon) was used to convert to reflectance. Absorption and beam attenuation coefficients (a, c) were measured at nine wavelengths (412, 440, 488, 510, 532, 555, 650, 676, 715 nanometers) using a WetLabs AC9 instrument. The instrument was calibrated prior to each deployment using milli-Q water, and the Zaneveld scatter correction was applied to all station data.[6] The scattering coefficient (b) is calculated by difference (c minus a). The data cover a broad range of absorption (0.04-4.0 m^{-1}) and scattering (0.01-14.0 m^{-1}) coefficients and remote sensing reflectance (0.001-0.02 sr^{-1}) in clear and turbid waters.

Table 2. Correlation results from *in-situ* and SeaWiFS R_{rs} using original NASA gain settings.

Band	R^2	Ratio	Gain
412	0.253	1.25106	1.0079
443	0.374	1.34956	0.9944
490	0.610	1.24780	0.9635
510	0.701	1.24249	0.9850
555	0.825	1.23841	0.9939
670	0.810	1.39401	0.9587

Comparison between Table 2 (original NASA gain settings) and Table 3 (newly-optimized NRL gain) shows that differences were observed in the gain settings for all channels. The average of all sums of the ratios (measured/*in-situ*) for each of the six SeaWiFS wavelengths was reduced considerably by iteratively calibrating the SeaWiFS sensor (gain values closer to one). The new gains shown in Table 3 were approximately one percent higher for the 412- and 510-nanometer bands and 1.65 percent higher for the 555-nanometer band. The correlation between *in-situ* measured and derived R_{rs} for each wavelength increased using the new gain settings, which indicates that the adjusted R_{rs} estimates from SeaWiFS are now closer to the *in-situ* R_{rs} measurements.

Using the new gain settings, the SeaWiFS reflectance values increase in the 412 and 443 channels, which is the spectral region where most of the negative reflectance values occur in turbid waters (due to inadequacies in the atmospheric correction algorithms over coastal waters). These adjusted gain values, coupled with the NIR atmospheric correction, help provide optical properties in bays and estuaries, where bio-optical algorithms previously failed.

Results

Results show that derived optical properties of absorption and scattering tend to be lower than measured values derived from SeaWiFS over all regions and wavelengths by approximately 49 percent and 59 percent, respectively. For both algorithms, the errors in turbid (higher absorption and scattering coefficients) waters were similar to the errors observed in clear waters.

Absorption errors for both algorithms are quite high and are due solely to the bio-optical algorithms because the vicarious gain settings have removed errors due to sensor calibration. The Arnone et al.[1] absorption algorithm tends to produce better results in the Gulf of Mexico and East Sea, whereas the Carder et al.[3] algorithm tends to do better in Tampa Bay. Both absorption algorithms produce similar errors in the New Jersey region.

Error results for both scattering algorithms are also quite high. The Arnone et al.[1] scattering algorithms for all four regions are less than those from the Carder et al.[3] algorithm. Overall, the Arnone et al.[1] algorithm generally yielded slightly lower errors and higher values for absorption and scattering than the Carder et al.[3] algorithms for the average percentage of both absorption and scattering coefficients

Table 3. Correlation results from *in-situ* and SeaWiFS R_{rs} using original NRL gain settings.

Band	R^2	Ratio	Gain	Change in Ratio (Percent)
412	0.425	1.00423	1.0179	+0.99
443	0.608	1.00015	0.9974	+0.3
490	0.792	1.00028	0.9623	-0.12
510	0.851	0.99883	0.9771	-0.80
555	0.900	1.00241	0.9775	-1.65
670	0.894	1.00763	0.9530	-0.59

SeaWiFS-derived optical properties (absorption and scattering coefficients) are lower than measured optical properties. The Arnone et al.[1] algorithm produced absorption and scattering coefficients closer to the measured values, as compared to Carder et al.,[3] for all wavelengths.

Even with improved gain settings, errors associated with the optical algorithms are quite high. For both optical algorithms, the errors in turbid (higher absorption and scattering coefficients) coastal waters were slightly greater than clearer open-ocean waters.

(46 percent versus 52 percent for absorption and 55 percent versus 63 percent for scattering) over all regions and wavelengths.

Summary

We compared *in-situ* measurements of R_{rs} a and b with SeaWiFS-derived values, and we derived new calibration gain settings for the SeaWiFS sensor. We subsequently applied these new gain factors to SeaWiFS imagery and compared results from two bio-optical algorithms. The new NRL calibration using revised gain factors produced SeaWiFS R_{rs} values closer to the *in-situ* measured R_{rs} values for all wavelengths. This calibration increased remote sensing reflectance values at 412 and 443 nanometers, but had a smaller effect at other wavelengths (510, 555 and 676 nanometers).

Future Efforts

We will continue collecting shipboard optical data sets in diverse environments to facilitate sensor validation and algorithm development efforts. New ocean color sensors, including existing and planned satellite and aircraft instruments such as MODIS, IKONOS, NEMO, PHILS and others, will provide high quality imagery at unprecedented spectral and spatial resolution. These new data sets will require advanced algorithms to take full advantage of the expanded information and to develop new products. This will enable us to explore oceanographic processes synoptically at finer scales.

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References

1. R.A. Arnone, P. Martinolich, R.W. Gould, M. Sydor, R. Stumpf and S. Ladner, "Coastal optical properties using SeaWiFS," Ocean Optics XIV, Kailua-Kona, Hawaii, 10-13 November 1998, Ocean Optics XIV CD-ROM (Office of Naval Research, Washington D.C. 1998).
2. P.M. Martinolich, *Automated Processing System User's Guide Version 2.4*, PDF Format, 2001.
3. K.L. Carder, F.R. Chen, Z.P. Lee and S.K. Hawes, "Semianalytic moderate-resolution imaging spectrometer algorithms for chlorophyll a and absorption with bio-optical domains based on nitrate-depletion temperatures," JGR, 104, C3, 5403-5421, 1999.
4. R.W. Gould, R.A. Arnone and M. Sydor, "Absorption, scattering and remote-sensing reflectance relationships in coastal waters: testing a new inversion algorithm," *Journal of Coastal Research*, 17, 2, 328-341, 2001.
5. J.R. Zaneveld, J.C. Kitchen and C. Moore, "The scattering error correction of reflecting-tube absorption meters," Ocean Optics XII Proceedings, SPIE 2258, 44-55, 1994.

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Richard Gould received a B.S. degree in oceanography from the Florida Institute of Technology in 1981 and a Ph.D. in oceanography from Texas A&M University in 1987. Gould has been conducting basic and applied research relating water bio-optical properties to multispectral and hyperspectral remote sensing reflectance data for the past 12 years at NRL. He has also developed and validated new coastal algorithms for ocean color aircraft and satellite sensors.

Paul Martinolich is a senior software engineer with Neptune Sciences Inc. with over 12 years of software development experience in remote sensing applications. He received a B.S. in mathematics in 1986 and an M.S. in mathematics in 1988, both from the University of Southern Mississippi. Martinolich designed and developed the automated processing system (APS) used by the NRL to automatically generate regional databases of ocean products from SeaWiFS, MODIS, AVHRR and CZCS data.